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FINAL REPORT AND THIRTEENTH
QUARTERLY REPORT ON CONTRACT
AF 04(647)-176
PENETRATION AND CRATERING

Technical Report UU-7
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ABSTRACT

This report is a summary of work done at the University of Utah High-Velocity Laboratory under Air Force Contract AF 04(647)-176 from 1 April 1958 to 30 June 1961. The work has been carried out in five phases:

1. A systematic investigation of the influence of target properties and projectile properties in high-velocity cratering and the formulation of empirical impact laws describing the results.

2. An investigation of penetration and perforation of thin target of aluminum and glass.

3. An experimental and theoretical investigation of the transient behavior in cratering, including an investigation of energy distribution and flow and wave motion.

4. A detailed theoretical and experimental investigation of elastic and plastic wave propagation in a rod.

5. An investigation of impact at velocities up to 25 km/sec utilizing micron-sized spray particles.

Results are summarized with references given to previously published reports. An outline of phases of the work which are continuing under contract AF 04(647)-952 is given.

- X -

CONTENTS

1. Introduction

This report is a final summary of work done at the University of Utah High Velocity Laboratory under Air Force contract AF 04(647)-176 covering the period 1 April 1958 to 30 June 1961. During this period, six technical reports were issued which serve as final reports on various phases of the work. One paper was presented at the Third Symposium on Hypervelocity Impact held in Chicago, Illinois, in October 1958, and one paper was presented at the Fourth Symposium on Hypervelocity Impact held at Eglin Air Force Base, Florida, in April 1960. These papers appear in the published proceedings of these symposia. These reports and papers are listed below. Their contents will be noted in the discussion of individual projects in following sections:

Technical Report UU-1, Perforation of Thin Aluminum Targets by Charles R. Morris, Wm. S. Partridge, and Emerson T. Cannon, August 1958.

Technical Report UU-2, Penetration and Perforation Studies of Thin Glass Targets by Merlin D. Fullmer, Wm. S. Partridge, and Emerson T. Cannon, August 1958.

Technical Report UU-3, Temperature Studies and Effects in Perforation of Thin Aluminum Targets by C. E. McDermott, E. T. Cannon, and R. W. Grow, May 15, 1959.

Technical Report UU-4, AFBMD-TR-59-21, Cratering Produced in Metals by High Velocity Impact by D. K. Johnson, E. T. Cannon, E. P. Palmer, and R. W. Grow, July 31, 1959.

Technical Report UU-5, AFBMD-TR-60-187, Projectile Effects and Subsurface Disturbance in High-Velocity-Impact Cratering in Lead by G. H. Turner, E. P. Palmer, and R. W. Grow, August 2, 1960.

Technical Report UU-6, AFBMD-TR-60-217, Investigation of an Arc Gun by T. Fujii, E. P. Palmer, and R. W. Grow, August 2, 1960.

"Perforation and Penetration Effects of Thin Targets" by W. S. Partridge, C. R. Morris and M. D. Fullmer, in Preceedings of the Third Symposium on Hypervelocity Impact, Armour Research Foundation, Chicago, Illinois, Vol. I, February 1959.

"Cratering: Experiment and Theory," by E. P. Palmer, R. W. Grow, D. K. Johnson and G. H. Turner, in Proceedings of the Fourth Symposium on Hypervelocity Impact, Air Proving Ground Center, Eglin Air Force Base, Florida, APGC-TR-60-39, Vol. 1, September 1960.

Quarterly reports have been issued to give an account of progress on the various research projects undertaken. A summary of information contained in them, which is not included in the technical reports, will be included in this report. Work done during the quarter 1 April to 30 June 1961 will be reported here.

Some of the results obtained from work done at the High-Velocity Laboratory under Air Force Office of Scientific Research contract AF 49(638)-462 have been used in furthering the work reported here. In particular, impact studies in lead, the development of light-gas-gun techniques, and the discovery of spray particles with velocities up to 20 km/sec have contributed to work under this contract (AF 04(647)-176). A list of technical reports issued under contract AF 49(638)-462 during the period of April 1958 to June 1961 is included here for reference.

Technical Report OSR-16, AFOSR No. TN-60-13, Spectral Analysis of the Impact of Ultra-Velocity Copper Spheres into Copper Targets by J. S. Clark, R. R. Kadesch, and R. W. Grow, September 1, 1959.

Technical Report OSR-17, Analysis and Development of a Light-Gas Gun for Accelerating Pellets to Hypersonic Velocities by K. E. Boyd, R. W. Grow, E. P. Palmer, and E. T. Cannon, October 15, 1959.

Technical Report No. OSR-18, Hypervelocity Impact Spray Particles by W. H. Clark, R. R. Kadesch, and R. W. Grow, May 1, 1960.

Technical Report No. OSR-19, AFOSR No. TN-60-989, Velocity and Size Distribution of Impact Spray Particles by R. E. Blake, R.W. Grow, E. P. Palmer, May 20, 1960.

Technical Report No. OSR-20, AFOSR No. TN-60-719, Preliminary Report on the Investigation of the Feasibility of an Electrostatic Accelerator for Accelerating Micron-Diameter Particles by G. K. Jesperson, D. W. Reid, R. W. Grow, and E. P. Palmer, November 15, 1960.

"The Anomalous Behavior of Lead to Lead Impact," by H. B. Van Fleet, W. S. Partridge, and E. T. Cannon in Proceedings of the Third Symposium on Hypervelocity Impact, Armour Research Foundation, Chicago, Illinois, Vol. I, February 1959.

"The Utah Light-Gas Gun," by W. A. Boyd, W. S. Partridge, and E. T. Cannon, in Proceedings of the Third Symposium on Hypervelocity Impact, Armour Research Foundation, Chicago, Illinois, Vol. I, February 1959.

"Experimental Investigation of Spray Particles Producing Impact Flash," by R. W. Grow, R. R. Kadesch, E. P. Palmer, W. H. Clark, J. S. Clark, and R. E. Blake in Proceedings of the Fourth Symposium on Hypervelocity Impact, Air Proving Ground Center, Eglin Air Force Base, Florida, APGC-TR-60-39, Vol. III, September 1960.

Work done under contract AF 04(647)-176 has supplied the material for six theses for the master's degree and has contributed to four others.

The research carried out under this contract has all been aimed at obtaining an understanding of high velocity impact phenomena sufficient to be able to explain observed effects, to quantitatively express the results in terms of measurable experimental quantities, and to derive fundamental laws which would allow extrapolation to new situations and new materials of scientific and engineering interest. Progress has been made toward these goals and the work is continuing under contract AF 04(647)-952.

During the course of the work, emphasis shifted as results were obtained and new discoveries made. The work was begun at a time when little experimental data on high-velocity impact was available and the first efforts were devoted to developing means for producing high-velocity impact, observing the results, and finding consistent ways to measure and describe the results. Semi-empirical formulas for describing the final results of impact were advanced and attempts made to substantiate the formulas and to find the important parameters affecting the results. This work was very similar to most other high-velocity impact studies being made throughout the country at this time as can be seen by reading the proceedings of the Third Symposium on Hypervelocity Impact.[13] The results obtained in these preliminary studies provided valuable engineering information

[13]References are given in the bibliography p. 7

- 3 -

and served as an introduction to the problems of hypervelocity impact. Because of the lack of a theoretical basis, the results could not be extrapolated to new conditions. Most of the work was done with a limited number of metals all of which fail in plastic flow, and impact velocities were all below 3.0 km/sec. The results obtained will be discussed in Section 2 below.

In an attempt to provide a better theoretical basis for impact studies, without attempting to actually solve the three-dimensional, transient flow-equations, a project was initiated to investigate the phenomena occurring in cratering in as much detail as possible and from this investigation to construct simplified models of the entire process. From these models, generalizations and extrapolations to other conditions could be made. An investigation of the distribution of energy among various competing processes in cratering and of wave propagation and material flow was begun. The results are discussed in Sections 3, 4, and 5.

Because of the complexity of the general cratering problem, it was decided to make a detailed study of wave propagation in a simple system, i.e., a rod. The results of this study have intrinsic interest as well as providing insight into the problems met with the more complex geometry of cratering. This work is discussed in Section 6.

In work done on impact flash under Contract AF 49(638)-462, it was discovered that micron-sized spray particles having velocities up to 20 km/sec are generated in ordinary low-velocity impacts. These particles have great potential value for use in impact studies at meteoric velocities, so a program was instituted to learn how to handle the particles, measure their size and velocity, and utilize them in impact studies. This work is described in Section 7.

Development of high-velocity projectile accelerators and firing range instrumentation has occupied considerable time. This work is discussed in Section 8.

2. Development of Empirical Impact Laws

Most impact investigations, particularly considerations of the general problem of cratering, have been experimental. This approach has been necessary because of the lack of theory of the transient flow of plastic-elastic media. The physical processes occurring are not well enough understood to allow complete general equations to be written. It is not certain that simplified equations such as the viscous-flow equations or the compressible-fluid equations commonly used in fluid dynamics are adequate to express the problem. Even if adequate, they are unsolvable in their general form. Further simplification leads to equations which may be solved numerically, but it is not known whether the resulting solutions really describe the original problem. Further simplification leads to theories which are at best just plausible estimates of the importance of various parameters affecting cratering. These expressions are characterized by the predominant role played by the experimentally determined "constants" appearing in the equations. Such expressions have been based on shaped-charge-jet theory, on target material properties, and on forces acting on a projectile Using these methods, useful correlations of various experimental data are obtained, but the understanding necessary to extend the rules to new conditions (particularly to higher velocities) is not forthcoming.

Experimental investigations of high-velocity impact have been mostly aimed at finding the numbers to use in simple equations or have been explorations made with the assumption that an understanding of

high-velocity phenomena could be obtained by shooting a few shots into well-chosen targets and observing the end results. It was hoped that the important physical laws would be immediately obvious if a simple program of systematically varying velocity and target and projectile materials was carried out. Experience has shown that such a program does not furnish enough information to allow the deduction of general laws, although the data collected are repeatable and allow engineering design to be made within the range of the data. High velocity impact phenomena turned out to be very complex with different results obtained in different velocity regimes. For example, for steel projectiles penetrating soft aluminum, the results shown in Fig. 1 are obtained. At low velocities, penetration occurs to great depths without projectile breakup. At higher velocities, the projectile deforms and the penetration decreases although velocity increases. In the next higher velocity region, penetration again decreases, projectile breakup is complete and holes became large in diameter and more shallow. At still higher velocities the craters are hemispherical and become larger in a regular manner as velocity is increased. In the range of meteor velocities, the shape and variation of shape with velocity are unknown. None of the simple rules used for correlating data apply over all velocity ranges. Because of the complexity of the problem, much of the past research has been devoted to materials which appear to fail in a simple manner, primarily in plastic flow where craters flow out smoothly without much spalling, cracking, or break-up in the region surrounding the crater. As a result of this restriction of materials, data again were limited, and general conclusions on a wide variety of materials could not be obtained. A discussion of the experimental investigations of cratering carried out at the High-Velocity Laboratory, University of Utah will be given in Sections 2.1 and 2.3 below.

(1)

0.63   0.98   1.39   1.52   1.62   1.96   2.27   2.38

(2)

0.67   1.06   1.33   1.37   1.59   1.83   2.08   2.28

(3)

0.55   0.86   1.06   1.23   1.44   1.95   2.18   2.33

(4)

0.32   0.63   0.97   1.47   1.66   1.83   2.09   2.23

(5)

0.63   0.99   1.34   1.51   1.60   1.97   2.19   2.30

(6)

0.57   0.82   1.10   1.36   1.73   2.00   2.16   2.50
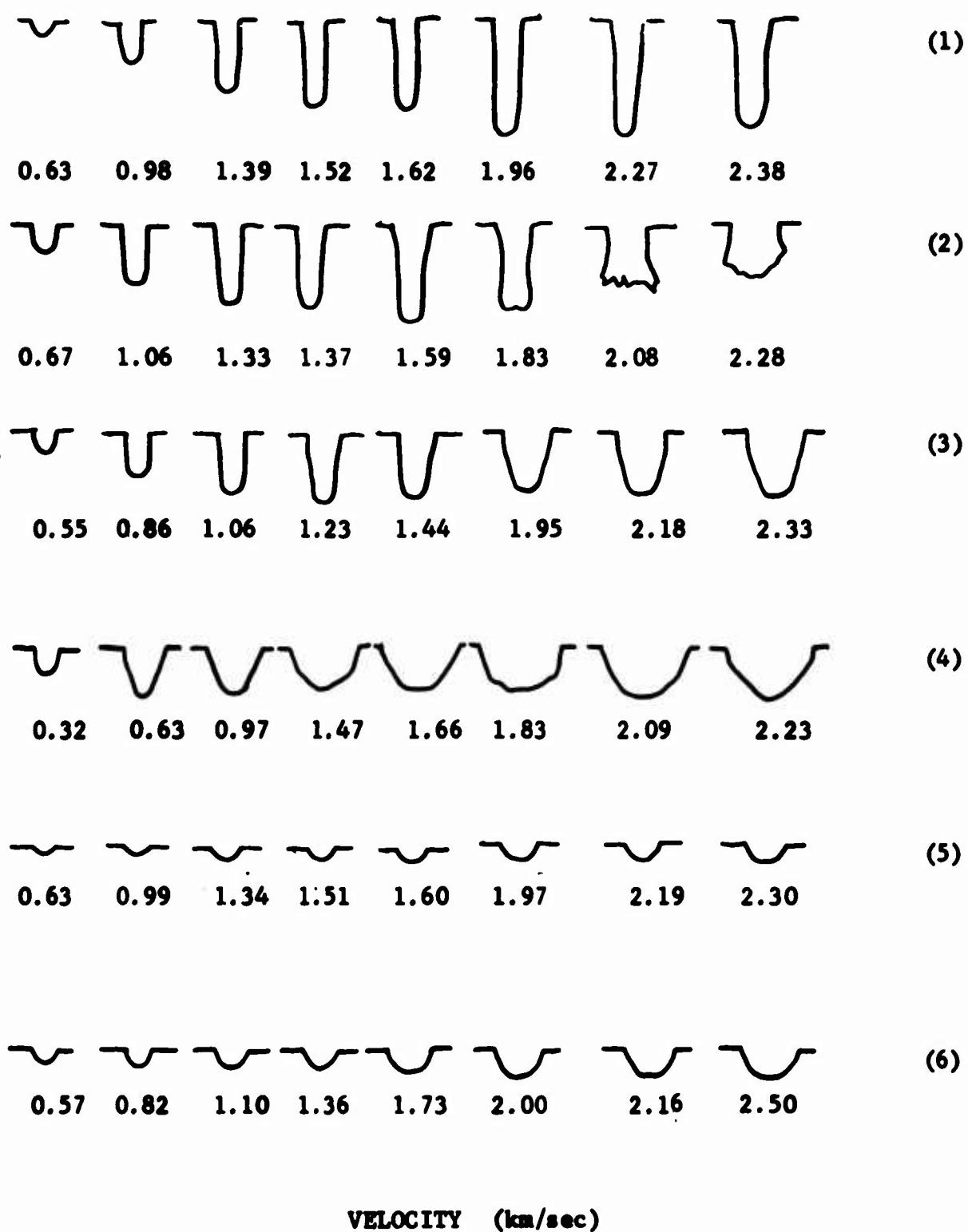
VELOCITY   (km/sec)

Fig. 1. Cross sections of craters produced by high-velocity impact. Crater lips were removed to facilitate measurements. Projectile diameter 3/16 inch (0.476 cm). (1) - Hardened steel into Mg. (2) - Hardened steel into Al. (3) - Annealed steel into Al. (4) - Hardened steel into Pb. (5) - Hardened steel into 4140 steel. (6) - Hardened steel into Cu.

In addition to cratering studies, experiments on the penetration of thin targets were conducted. This work is reported in Section 2.4 below.

2.1 Investigation of the effects of target properties on high-velocity-impact cratering.

The purpose of this project was to determine the effects of varying target properties on cratering in high velocity impact. By a systematic study of cratering at various velocities in various targets, it was hoped to be able to determine the manner in which target material-properties enter into the formulation of a general, empirical, impact theory. This goal has been partially met although the results have limited validity, being restricted to materials which fail primarily in plastic flow and to velocities below 2.5 km/sec. The work was done by shooting spherical projectiles of hardened steel or annealed steel into targets of iron, copper, aluminum, magnesium, tin, zinc, and lead. The details of experimental methods and results are given in Technical Report UU-4.[4]

Cross sections of typical craters are shown in Fig. 1. The crater lips have been removed to facilitate depth, area, and volume measurements. The onset of projectile deformation or break-up can be determined and related to the way in which penetration and crater area vary with velocity. These experiments yield the now familiar result that, in this velocity range, crater volume is proportional to projectile energy. This is independent of projectile deformation or shattering. Values of volume per unit energy are given in Table 2 in Section 2.3 along with other data.

For these experiments, a fairly adequate explanation results from

- 8 -

assuming that the target will withstand a certain constant pressure
before yielding and that the total work done is equal to this pressure
multiplied by the area over which it acts and the displacement occurring.
This may be written

$$E = P \int_0^{x_0} A(x) \, dx$$

where
$\quad\quad E$ = energy of projectile
$\quad\quad P$ = pressure for deformation
$\quad A(x)$ = area over which pressure acts
$\quad\quad x$ = depth coordinate
$\quad\quad x_0$ = depth of penetration

If the area over which the pressure acts, $A(x)$, is assumed to be
proportional to the crater area, $A_c(x)$, the following expression results

$$E = PK \int_0^{x_0} A_c(x) \, dx \quad .$$

The integral is the volume of the crater, V, thus

$$\frac{V}{E} = \frac{1}{KP} \quad .$$

If P is chosen as the shear strength of the material, the following
values are observed for K.

Material	K
Lead	19.7
Aluminum	9.3
Magnesium	9.2
Zinc	11.7
Copper	10.5
4140 Steel	9.0

The discrepancy with lead probably indicates that the cratering
process is more strongly influenced by the high density, low strength,
low melting temperature, and low heat of fusion of this material than

- 9 -

is indicated in the above simple analysis.

Projectile break-up serves as a measure of maximum pressure generated in the impact. If stagnation pressure, P_s, on the projectile is assumed to be given by the Bernoulli equation, $P_s = \frac{1}{2} \rho_t v^2$, where ρ_t is target density and v is impact velocity, it is observed that P_s is very close to 3.8×10^9 newton/m^2 (574,000 lb/in^2) for all cases. This is illustrated in Fig. 2 where v is plotted versus ρ_t for the point of projectile break-up in each material. The manufacturer of the ball-bearing projectiles gives a value of 287,000 psi for their ultimate tensile stress. The stagnation pressure, P_s, at break-up is twice this value.

Penetration and crater area (or crater shape) are strongly influenced by projectile deformation and break-up and can not be simply correlated with other parameters over a wide range of conditions. It was found that crater area is proportional to projectile momentum for limited velocity ranges. For some materials, the constant of proportionality changes value abruptly at the velocity where projectile deformation becomes pronounced. Penetration is likewise proportional to momentum over limited regions with the constant of proportionality changing as the mode of cratering changes. Figures 3 and 4 illustrate this behavior. It is noteworthy that the ratio of crater volume to projectile energy remains constant through all these wild fluctuations in crater shape.

The utilization of these results in a more general cratering theory will be discussed in Section 2.3 below. The limitations on the conclusions which may be drawn from this work and possible extensions of the work will be considered.
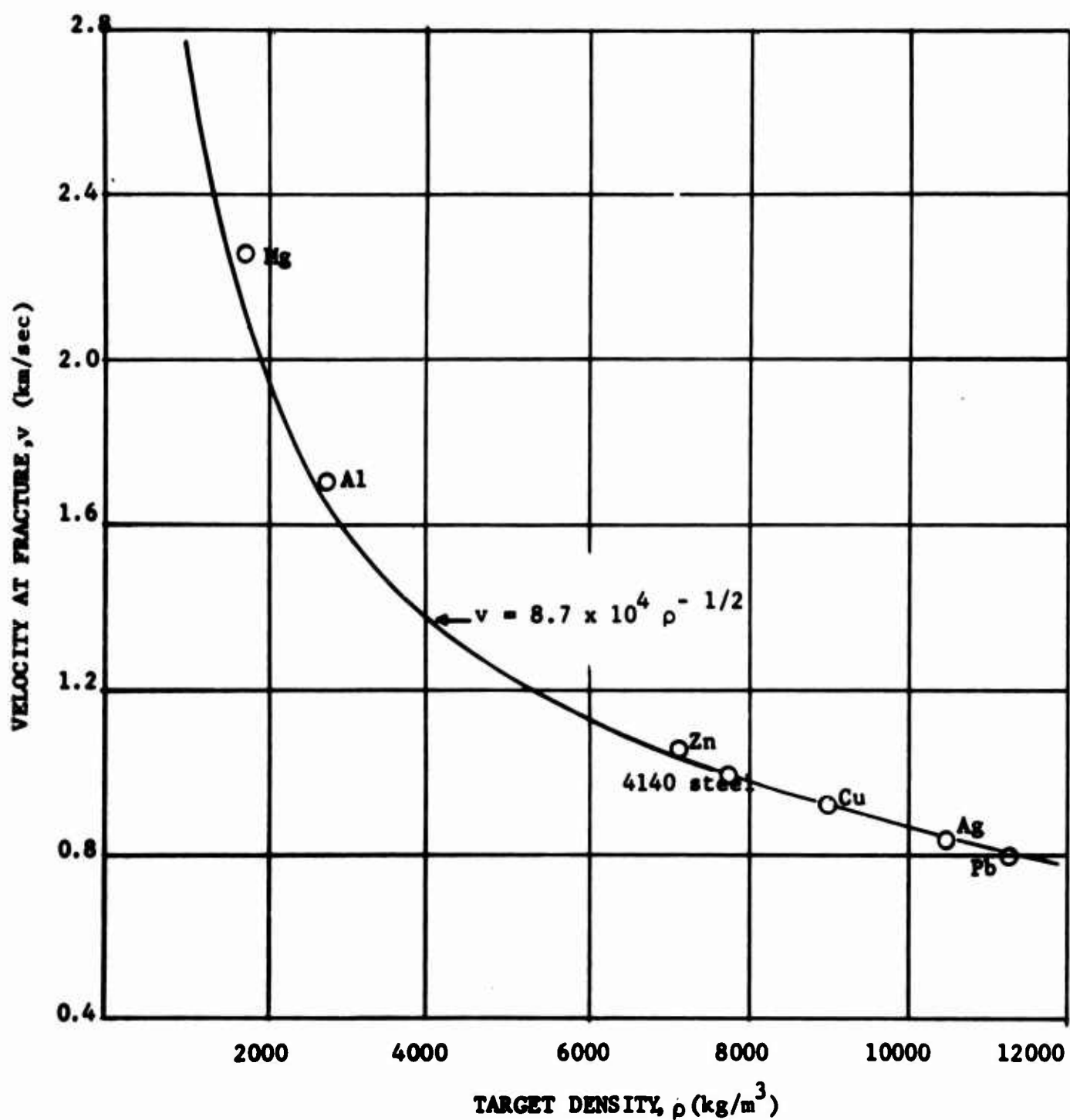
VELOCITY AT FRACTURE, v (km/sec)

2.8

2.4

○ Mg

2.0

○ Al

1.6

$v = 8.7 \times 10^4 \rho^{-1/2}$

1.2

○ Zn
4140 steel
○ Cu
Ag
Pb

0.8

0.4

2000   4000   6000   8000   10000   12000

TARGET DENSITY, ρ (kg/m^3)

Fig. 2. Velocity of projectile fracture versus target density
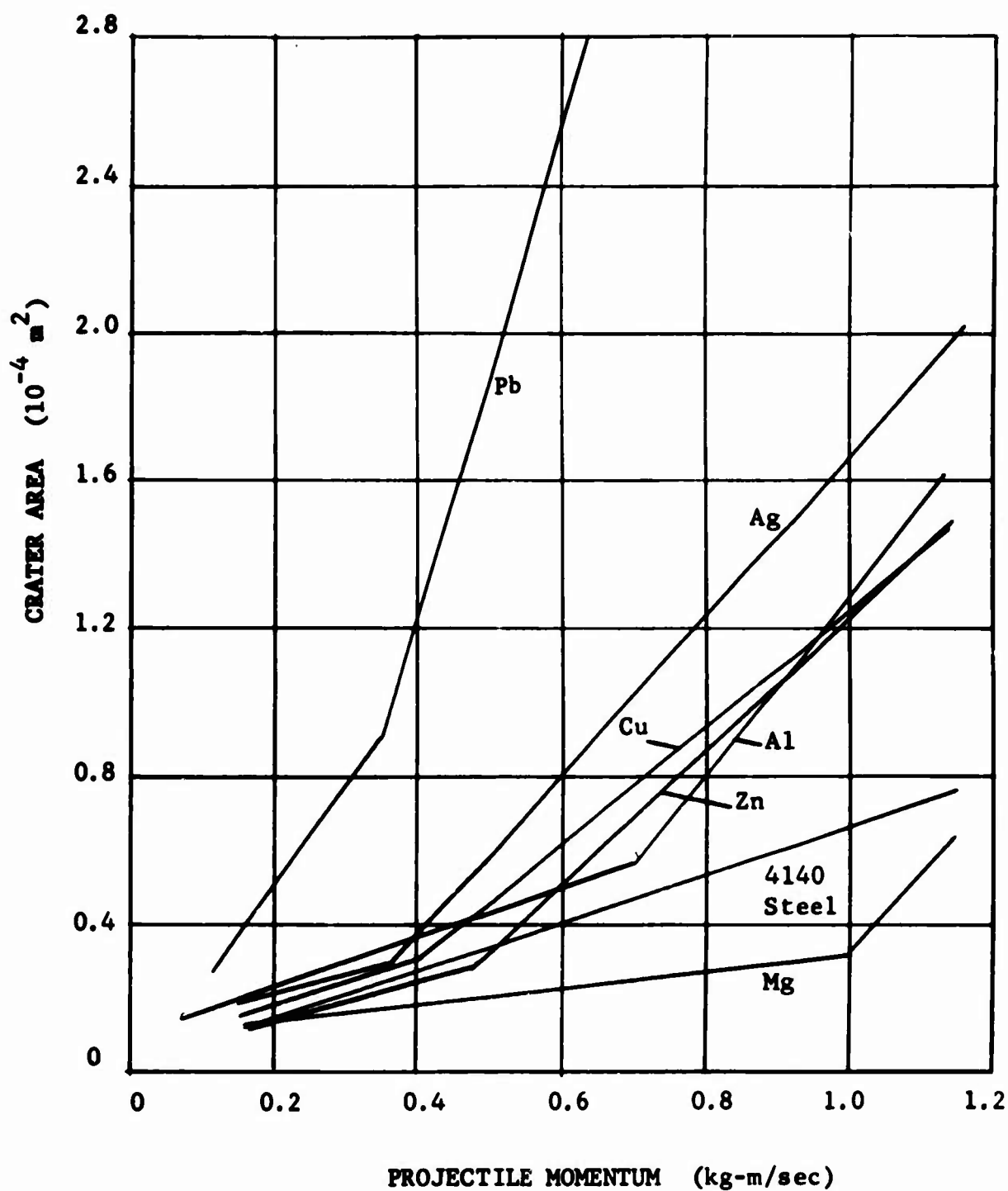for hardened chrome-steel projectiles.

Fig. 3. Crater area versus projectile momentum for hardened, chrome-steel spheres impacting into various materials.
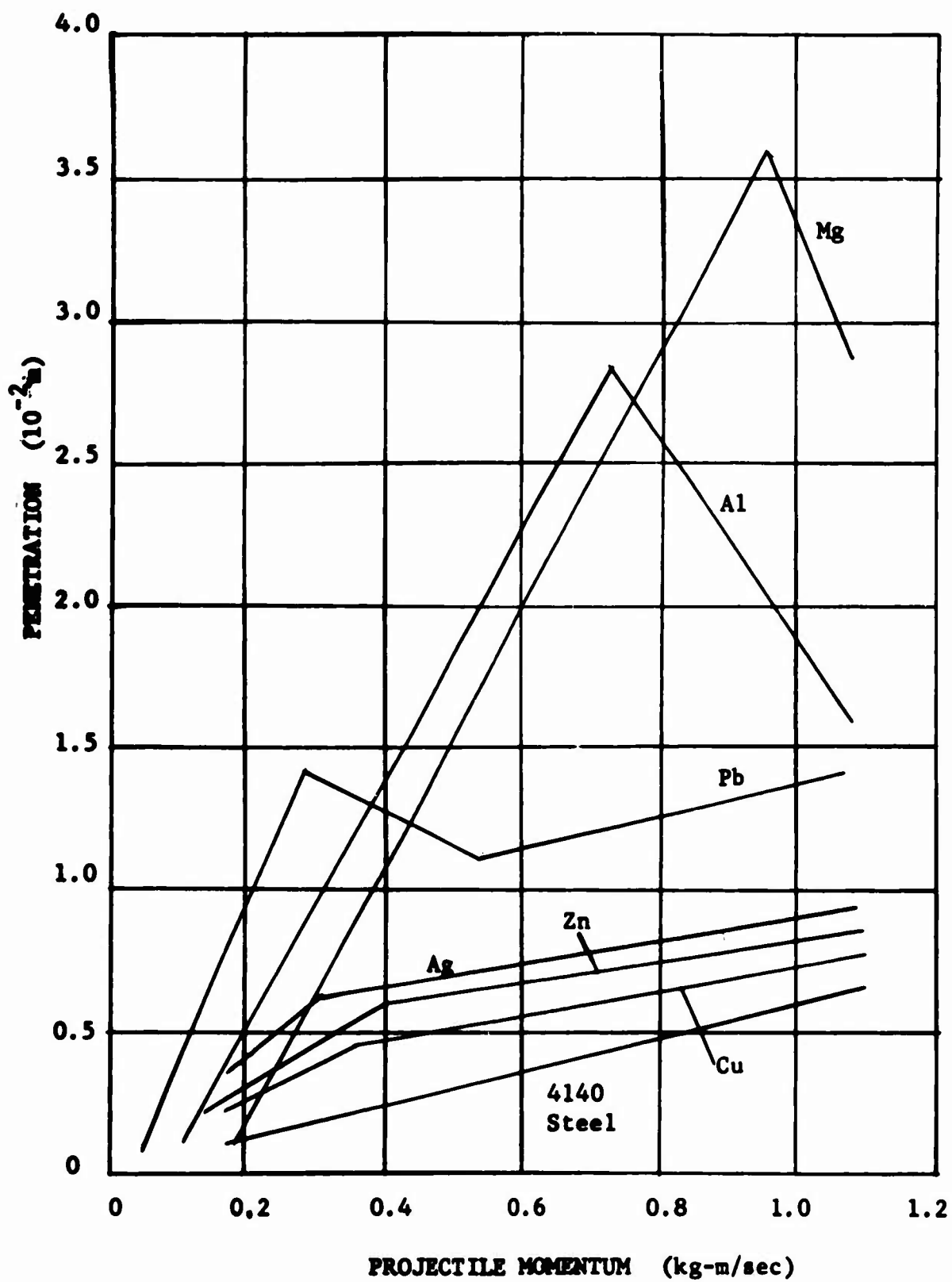
Fig. 4. Penetration versus projectile momentum for hardened, chrome-steel spheres impacting into various materials.

2.2 Investigation of the effects of projectile properties on high-velocity-impact cratering.

The purpose of this project was to determine the effects of varying projectile properties on high-velocity impact. Like the study of varying target properties, this work was concerned with an attempt to discover generally valid impact laws. A systematic study was made of the cratering produced in lead by projectiles of 13 different materials. These studies are limited to velocities below 2.5 km/sec and by the fact that only one target material was used. However, the work constitutes the most complete study of the effects of projectile properties made up to the present time and reveals the importance of projectile effects in cratering. These effects have been often neglected in empirically-derived impact theories based primarily on target properties. The details of experimental techniques and results are given in Technical Report UU-5.[5]

Crater volume was found to be proportional to projectile energy for each projectile; however, considerable difference in the value of V/E was found when comparing different projectile materials. The results of this study are shown in Table 1. It is seen in Fig. 5 that V/E is approximately proportional to the square root of projectile density. The effects of projectile strength, independent of density, are observed in the three shots with steel. The harder, tougher chrome-steel produces the largest crater. Such systematic comparisons with other materials cannot be made because of the limited data.

In this investigation of projectile properties, it was found that crater area is a linear function of projectile momentum for each projectile material. This is the same result as that discussed in Section 2.1 for

TABLE 1. Crater volume per unit projectile energy for
various projectiles impacted into lead.

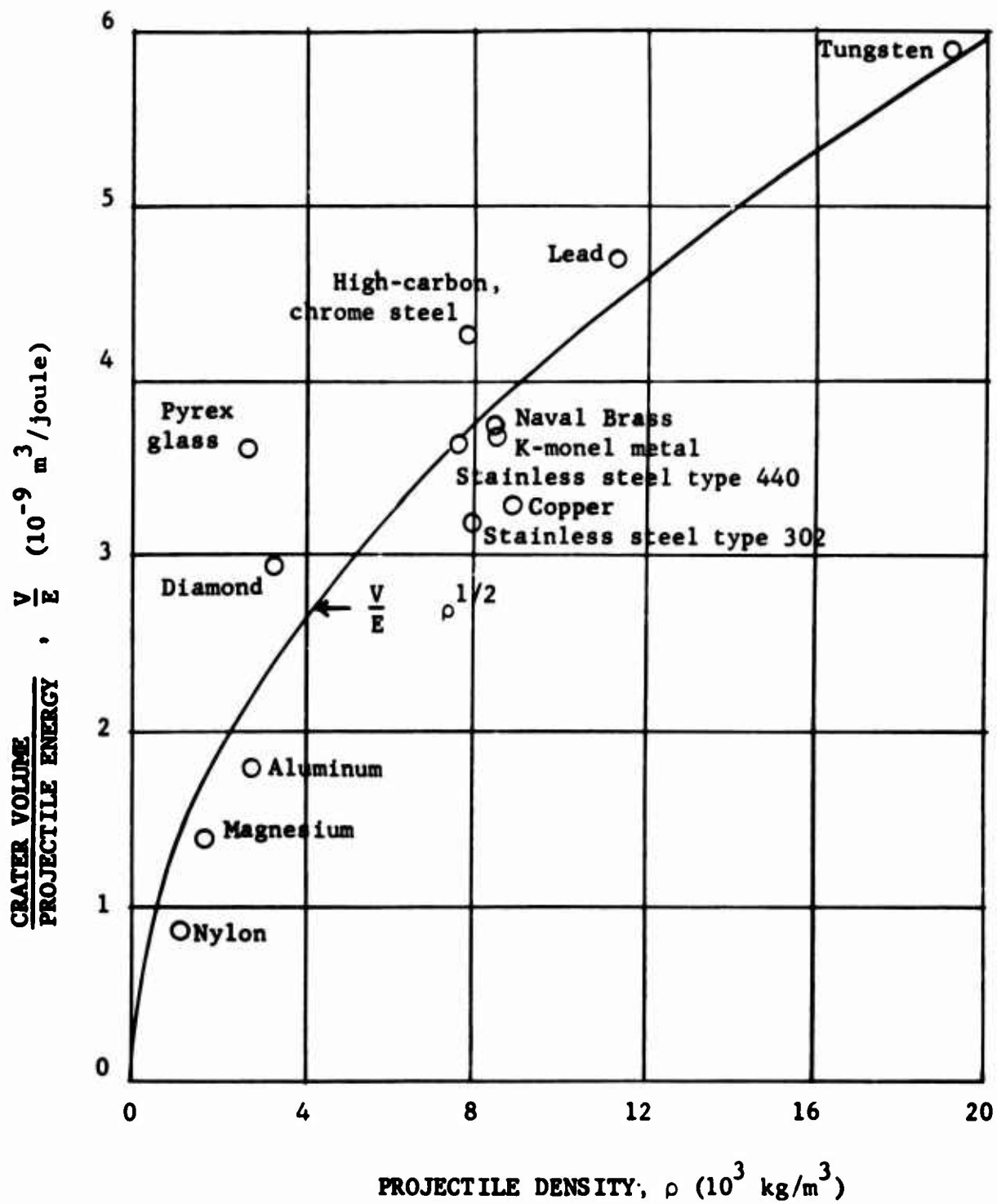| Projectile Material	Volume/Energy (meters^3/joule)	Projectile Density (Kg/meter^3)
Nylon	0.87×10^{-9}	1.16×10^{-3}
Magnesium	1.40	1.74
Pyrex glass	3.63	2.64
Aluminum	1.81	2.80
Diamond	2.96	3.30
Stainless steel type 440	3.65	7.63
High carbon, chrome steel	4.25	7.85
Stainless steel type 302	3.21	7.90
Naval brass	3.76	8.45
K-monel metal	3.71	8.48
Copper	3.30	8.90
Lead	4.70	11.34
Tungsten	5.89	19.20

Fig. 5. Crater volume per unit projectile energy versus projectile density for impact into lead.

steel projectiles into various targets. Crater shape in the lead targets has a certain regularity as indicated by the relationship between crater depth, p, and the ratio of volume to area, V/A. This relationship is indicated in Fig. 6. These results may be summarized by the following equations:

Crater volume is proportional to projectile energy E.

$$V = i_1 + k_1 E \qquad (2.1)$$

Crater area is proportional to projectile momentum M.

$$A = i_2 + k_2 M \qquad (2.2)$$

Penetration is proportional to the ratio of volume to area

$$p = 1.7 \ V/A \qquad (2.3)$$

The constants i_1, i_2, k_1 and k_2 are dependent upon the projectile material and can be adequately expressed as linear functions of projectile density only; thus, crater volume, area, and penetration are functions only of projectile size, density, and velocity. (See Technical Report UU-5 for a detailed analysis of these results.) Values of the constants are given by the following expressions where ρ is projectile density. M.K.S. units are used.

$$i_1 = -0.025 + 0.031 \times 10^{-3} \rho$$
$$i_2 = 0.27 - 0.11 \times 10^{-3} \rho$$
$$k_1 = 4.2 \times 10^{-5} \rho^{1/2}$$
$$k_2 = 6.0 - 0.080 \times 10^{-3} \rho$$

Using these values in Eqs. 2.1 and 2.2 and combining them in Eq. 2.3, we may compare the computed values of penetration with those actually observed. The results are shown in Fig. 7. For most practical purposes i_1 may be neglected and k_2 may be considered constant with a value of 5.5.

Fig. 6. Crater depth versus crater-volume divided by crater-area for nylon, copper, and tungsten projectiles impacted into lead. Results for other projectiles are similar but are omitted for clarity.
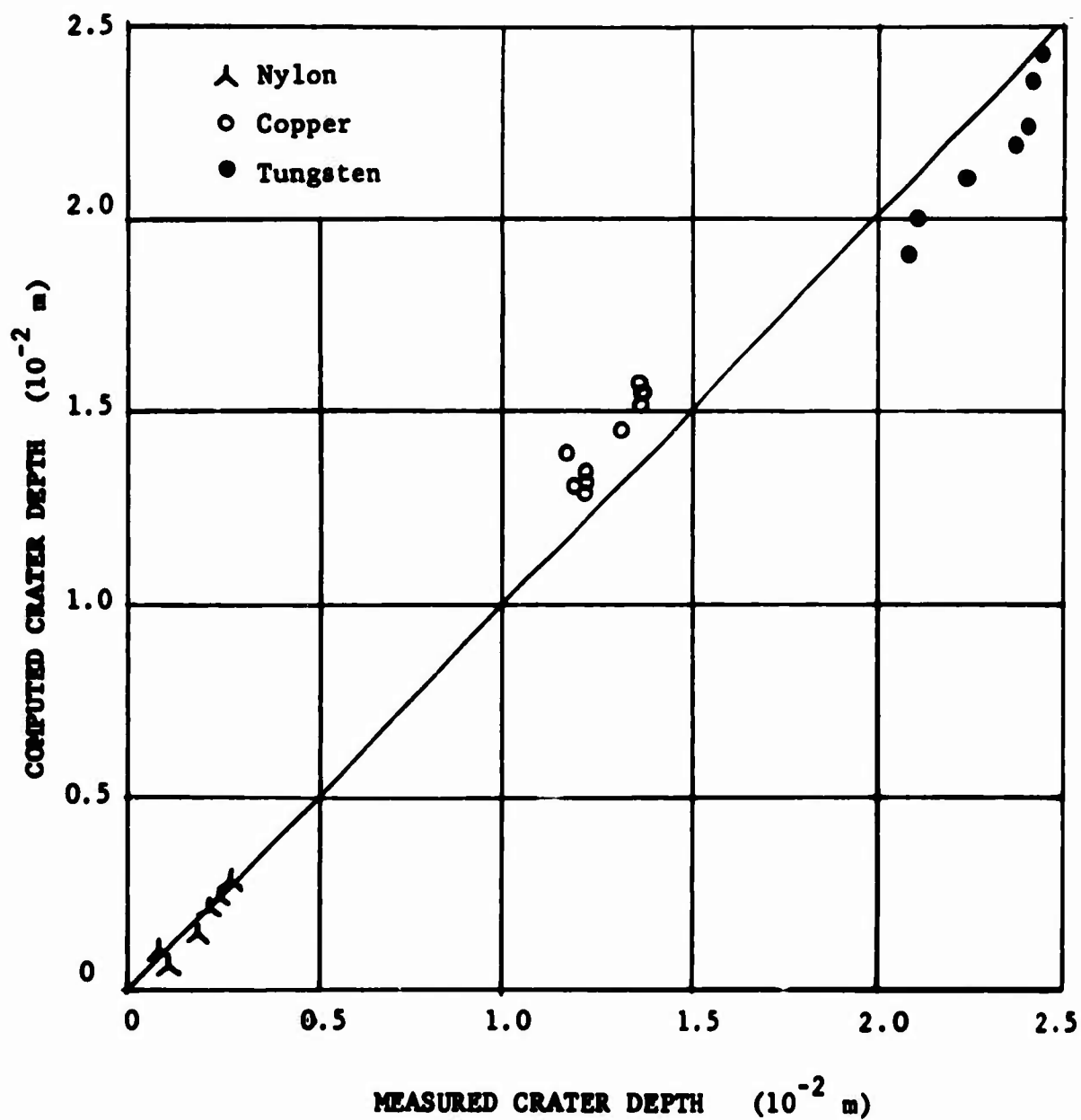
Fig. 7. Computed crater depth versus measured crater depth for impact into lead. Results for other projectile materials are similar but are omitted for clarity.

It must be noted that these results apply only to cratering in lead within the velocity range up to 2.5 km/sec. More general relationships will be discussed in the following section. These results indicate that adequate expressions for design information can be derived if data are available. The weaknesses of the method are apparent: only limited trust can be put in any extrapolations outside the range of the data; if the data are available the formulas may be superfluous; only little insight is given into the understanding of more general problems.

Additional comments on lead cratering can be made from the results of work done under contract AF 49 (638)-462. For impacts of lead on lead, earlier work showed that all crater dimensions are proportional to projectile dimensions; thus size scaling is valid. For all sizes it appeared that crater volume per unit projectile energy began to decrease at velocities above about 1.5 km/sec and approached the condition that volume was proportional to momentum rather than energy. It was thought that these results might tend to substantiate Bjork's theory of cratering[15] which predicts volume proportional to momentum for cratering in iron and aluminum at velocities above 5.5 km/sec. Recent work has cast doubt on these conclusions concerning lead, and it may be that projectile deformation and break-up before impact cause the decrease in the ratio of volume to energy. In carefully conducted measurements, it was found that many craters follow the straight-line relationship between volume and energy and those that drop below may do so because of defects in the projectile. However, the matter is not settled because all the scatter in data occur below the line of constant volume to energy ratio. An answer to this question awaits the development of better means of accelerating weak projectiles to higher velocities.

2.3 Development of impact laws and analysis of results.

Many laboratories have spent much time in obtaining experimental impact data and attempting to derive satisfactory impact laws. About the only sure conclusions that can be drawn from the work are that bigger projectiles produce bigger holes, "tougher" projectiles produce bigger holes, and "tougher" targets result in smaller holes. The problem comes in trying to adequately measure "toughness" and relate it to material properties. Many measures of "toughness" such as Brinell hardness, tensile strength, shear strength, compressive yield strength, heat of fusion, and speed of sound have been used with apparent success under limited conditions. An understanding of why such diverse quantities can be used to give similar results awaits a better understanding of the actual processes involved in cratering.

A simple law relating crater volume to projectile energy which is probably as successful as any previously advanced in correlating all presently available impact data may be derived from the experiments discussed in Sections 2.1 and 2.2 above. This work indicates that V/E is proportional to the square root of projectile density and inversely proportional to target shear strength P_t.

$$V/E = \frac{k \, \rho_p^{1/2}}{P_t} \tag{2.4}$$

Written in terms of crater radius R (radius of a hemisphere with volume equal to V), projectile radius r, and velocity v, this becomes

$$\frac{R}{r} = \frac{k^{1/3} \, \rho_p^{1/2} \, v^{2/3}}{P_t^{1/3}} \tag{2.4a}$$

- 21 -

An average value for K is found to be 7.3 x 10^{-4} where all quantities are expressed in M.K.S. units.

Efforts have been made to compare the impact theories and results reported by various other workers with those obtained in this laboratory. In general, similar results are obtained. This is to be expected since the properties used in the various "laws" to correlate and explain the results are related. For example, Summers and Charters have used impact "Mach number," or impact velocity divided by speed of sound in the target as the important parameter determining impact behavior.[16] They give the equation

$$\frac{R}{r} = 4.56 \left(\frac{\rho_p}{\rho_t}\right)^{2/3} \left(\frac{v}{c}\right)^{2/3} \tag{2.5}$$

where ρ_t is target density and c is the velocity of sound in the target. Written in terms of crater volume per unit projectile energy, this becomes

$$\frac{V}{E} = 95 \frac{\rho_p}{\rho_t^2 c^2} \tag{2.5a}$$

Robert Bromberg has suggested that Charters' data can be explained by means of a simple model in which the impact energy all goes into breaking bonds in the target material after which material flows from the crater without requiring much additional energy. The energy required to "loosen" the bonds should be approximately the same as that required to loosen them by means of heat. Thus, heat of fusion should be the

important parameter in explaining impact. The equation expressing this is

$$V \rho_t L = E \qquad (2.6)$$

where L is the heat of fusion of the target. Written in terms of crater radius, this is

$$\frac{R}{r} = \left(\frac{\rho_p}{\rho_t} \right)^{1/3} \frac{v^{2/3}}{L^{1/3}} \qquad (2.6a)$$

A comparison of Eqs. 2.5 and 2.6a indicates that, for equal target and pellet density, the following relation should hold if the two theories are to agree.

$$\frac{4.56}{c^{2/3}} = \frac{1}{L^{1/3}}$$

or

$$c^2 = 95L \qquad (2.7)$$

A plot of Eq. 2.7 showing the values of c^2 and L for some materials is shown in Fig. 8. It is seen that for most ordinary materials, there is an approximately linear relationship between c^2 and L; thus if one equation is valid, the other must be also.

There are many materials which do not closely obey the relationship between speed of sound and heat of fusion given by Eq. 2.7. Examples, among the elements, are beryllium and silicon. It would be
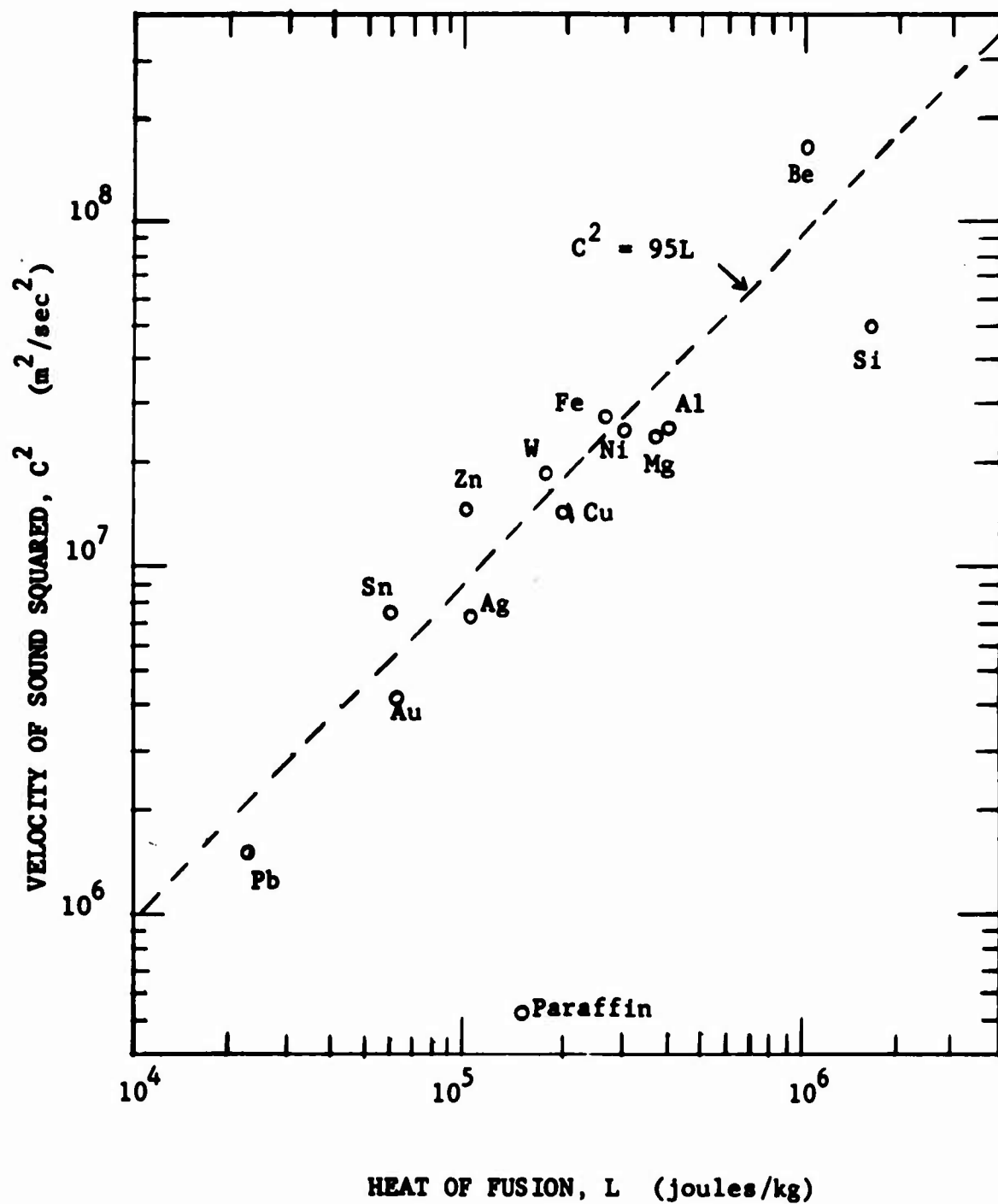
Fig. 8. Velocity of sound squared versus heat of fusion for various materials.

enlightening to do impact studies in these materials or with others which are not "ordinary" as determined by Eq. 2.7. Work with these materials should help determine whether Eq. 2.5 or 2.6 is more fundamental in expressing impact behavior or if either is really significant.

A comparison of Eqs. 2.4, 2.5 and 2.6 with experimental results is given in Table 2. It is seen that each of the "laws" has merits and failings. Charters' expression generally predicts a value of V/E, which is too large, it does not adequately account for projectile properties, and fails particularly in cases of low target density.

Bromberg's expression does not account for the influence of projectile properties on cratering, so fails particularly in explaining the lead data where the projectile is varied. The High Velocity Laboratory expression is based on shear strengths which are highly variable. The values shown are handbook values and may not agree too closely with the actual values of the targets used. The influence of projectile properties is also not adequately accounted for by the square-root-of-density factor.

Whether or not any of the impact "laws" described above are adequate for a particular engineering purpose must be determined by the user. It must be recognized that the discrepancies between theory and experiment, limited material coverage, narrow velocity range, and lack of a theoretical basis make all the relationships useless as a general expression of the impact process. Extrapolation to other conditions and materials must be done with caution.

Materials: Projectile Into Target	Exper. V/E $(m^3/joule)$	Hi-Vel.Lab $V/E = 7.3 \times 10^{-4} \left(\dfrac{\rho_p}{P_t} \right)^{1/2}$	Bromberg $V/E = \dfrac{1}{\rho_t L}$	Charters $V/E = \dfrac{\rho_p}{\rho_t^2 c^2}$
Cu → Cu	$.588 \times 10^{-9}$	$.436 \times 10^{-9}$	$.551 \times 10^{-9}$	$.763 \times 10^{-9}$
Pb → Pb	4.80	6.46	3.81	5.74
Al : Al	.776	.584	.918	1.41
Fe → Fe	.282	.215	.471	.448
Sn → Sn	1.104	3.11	2.30	1.75
Zn → An	.596	.47	1.37	.90
Ag → Ag	.800	1.24	.91	1.26
Be · Be			.513	.316
Si → Si			.382	.861
RC 66 Steel				
→ Pb	4.25	5.39	3.81	3.97
→ Al	1.67	.966	.918	4.09
→ Mg	.86		.91	.94
→ Mg	.84	.494	1.52	10.1
→ Zn	.65	.494	1.37	.99
→ Cu	.60	.410	.551	.67
4140 Steel	.20	.118	.471	.45
Annealed Steel				
→ Al	1.55	.996	.918	4.09
→ Cu	.52	.410	.551	.67
Nylon → Pb	.87	2.07	3.81	.585
Mg · Pb	1.40	2.53	"	.88
Pyrex Glass Pb	3.63	3.12	"	1.33
Al Pb	1.81	3.16	"	1.36
Diamond → Pb	2.96	3.49	"	1.67
Steel 440 Pb	3.65	5.31	"	3.85
HiC-C Steel - Pb	4.25	5.39	"	3.96
Steel 302 → Pb	3.21	5.41	"	3.99
Naval Brass → Pb	3.76	5.59	"	4.27
W → Pb	5.89	8.43	"	9.70
Cast 50% Pb, 50% Sn	1.70	1.74	"	9.70
Cast 40% Pb, 60% Sn	1.65	1.58	"	
Mold 40% Pb, 60% Sn	1.86	1.58		
Mold 50% Pb, 50% Sn	1.96	1.74		
Wax Wax	24.0		6.58	186.3

This experimental approach to the problem of obtaining valid
impact laws is fruitful even though wasteful, and it should be continued
and extended, particularly since no other approach has yet given valid
results. The extension must be made to higher velocities and to many
different types of materials.

Work of this type is continuing at the University of Utah under
contract AF 04(647)-952. Spray particles are being used to extend
velocities up to 25 km/sec (See Sec. 7 below), and experimental
investigation of the detailed physical processes involved in cratering
is being done. This is discussed in Sections 3, 4, and 5 below.

2.4 Penetration of thin targets by high-velocity projectiles

This project was concerned with an experimental investigation of the penetration of thin targets by high-velocity projectiles. The goals were to obtain useful engineering information on damage to thin structures and to derive general penetration laws. The results are of interest in themselves and have interesting applications in the development of "meteor bumpers" and other devices for protection against fast particles.

It was considered possible that the results of penetration studies in thin targets could be applied in a step-wise fashion to solve the more general problem of cratering in thick targets. The results of the investigation proved that this was not practical and that the complex phenomena met in the general three-dimensional problem of cratering are not approximated by thin-target results. The details of this work are given in Technical Reports UU-1, UU-2, and UU-3 listed on page 1.

In this study, steel spheres were impacted against aluminum targets having various thicknesses and at various temperatures. Velocities ranging up to 3 km/sec were used. It was found that for target perforation the energy lost by the projectile in passing through the target was proportional to the initial energy. The minimum velocity of penetration was found to be a linear function of target thickness. Similar results were found for steel projectiles penetrating glass targets. For the aluminum targets, the results could be explained by assuming that the projectile melted its way through the target.

The work on thin-target penetration should be extended to satellite and meteor velocities to be very useful. It is not to be expected that the results found in the studies reported here will be applicable at higher velocities.

3. Investigation of the Physical Processes in Cratering and the Development of Cratering Models

This project is concerned with finding and quantitatively measuring the important physical processes occurring in cratering, in determining how these processes change for different materials and different impact conditions, and in relating these processes to measurable material properties. This information is to be used in constructing simplified models of the cratering process which embody the necessary physical detail and agree with experimental data. The final form of the models will be mathematical expressions of impact laws.

The failings of theory and experiment in impact studies have been briefly discussed in Sections 1 and 2 above. In summary, it may be said that theory has failed because of the complexity of the processes. No one has been able to comprehend all the details and their interrelations and bring order out of chaos. Experiment has failed because of the simplicity of the approach; by looking only at "before" and "after" conditions, all that happens in between is neglected. With this in mind, it seems likely that a middle approach could prove fruitful; that of attempting to account for the most important of the transient processes occurring during cratering and embodying them in simplified, yet detailed, theories and models.

To begin this approach, attempts were made to draw pictorial models of the cratering process. Simplified flow patterns were drawn to connect the initial undisturbed state of the material with the final crater. From these models, the material involved in motion and the amount of motion can be determined. It became immediately evident that almost all the necessary information for constructing such a model was missing.

In particular, in this first step of just going from the beginning to the end of the process and neglecting the details of in-between processes, it was realized that the final state of the crater is unknown. No information has ever been gathered on how much of the projectile remains in the crater, how much target material is lost, or how much of the displaced material is pushed up into the lip and how it is distributed in the lip. This information could have been fairly easily obtained on all past shots but can only be obtained now through further experimentation. In drawing the flow patterns, no guiding information is available. It is not known whether flow occurs primarily from a thin layer in rapid motion or whether the entire crater volume is quickly involved and the flow occurs more slowly from a thicker region. It is not known whether penetration is initially deep or shallow with subsequent slow enlargement of the crater or whether the process is more uniform. It is not known how much of the projectile energy is lost from the cratering process through various types of wave motion in the target.

The strength of this method is revealed in the questions which it raises. The most fundamental questions of energy distribution and material flow have apparently never been asked before. If asked, no serious attempts have been made to answer them, probably because no model was being developed for utilization of the answers. It seems unlikely that cratering theory will advance until the standard technique of science, that of conceiving a plausible model and refining it through theoretical and experimental investigation, is applied. Some information applicable to cratering problems is available. Investigations of elastic, plastic, and shock-wave propagation in materials have been made.[17] It is expected that this information can be integrated into the cratering problem.

To support this program of a detailed investigation of the transient flow in cratering, two projects have been initiated -- one to determine the energy distribution in high-velocity impact and the other to determine material flow and wave propagation. These projects will be discussed in Sections 4 and 5 below.

4. Energy Distribution in High-Velocity-Impact Cratering

This project is concerned with determining the distribution of energy among the various competing processes occurring in cratering and with determining the effects of different material properties and impact velocities on this energy distribution. The purpose is to provide information necessary for formulating impact theory from models which adequately describe the physical processes involved.

For preliminary investigations of energy distribution, the projectile energy may be divided in the following way:

1. Energy escaping from the system as kinetic energy and internal energy (heat) of material which leaves the target. This material may be from target or projectile.

2. Energy going into deformation of target and projectile.

3. Energy escaping from the crater vicinity into the surrounding target, primarily by wave motion.

4. Energy going into structural changes such as recrystallization in the crater vicinity.

5. Energy escaping as acoustic or electromagnetic radiation to the surroundings or conducted away as heat.

These processes are all interrelated and these particular divisions are arbitrary. Experience with measurements will probably show that other

divisions are more appropriate. These are dictated by a simple model in which only gross overall features are recognized. The energy of cratering is mainly that listed under 1 and 2 on the previous page. The others represent losses from the process. That listed under 5 is negligible in influencing cratering but may be of primary importance for other problems such as meteorite detectors depending upon light flash, etc.

Work has begun on measuring the energy distribution for cratering in lead. The work so far has been exploratory to develop techniques and instrumentation and to assess the problems. It was observed that considerable recrystallization of target material occurs in the region surrounding a crater in lead. This is produced by mechanical deformation and not heat. In order to measure the energy going into recrystallization, artificial craters were formed by pressing a steel ball into a lead target. Measuring the work done and the amount of new crystal surface formed, it was possible to place an upper limit on the energy of recrystallization. The details of this preliminary work have been reported in Technical Report UU-5 referred to on page 1. To refine these measurements, lead blocks were instrumented with thermocouples and the amount of energy appearing as heat was measured. The results show that from 12 to 15 per cent of the energy goes into recrystallization and the rest into heating of the block. Careful measurements of the amount of recrystallization are being made in order to determine the specific energy of recrystallization. This information will be applied to impact-produced craters to determine the energy going into this form. Preliminary estimates indicate that from 5 to 10 per cent of the projectile energy goes into recrystallization for shots with a velocity of 2 km/sec.

The next step in this project was to measure the amount of energy escaping from the target as kinetic energy and internal energy of spray particles. This was done by instrumenting targets with thermocouples and measuring the temperature rise upon high-velocity impact. These measurements proved difficult to make because of the small temperature change involved, but they have at least shown the feasibility of the method. Measured energy losses range from 10 to 50 per cent. The percentage loss depends upon projectile velocity, but scatter in the data prevents any definite conclusions to be made at this time as to the exact form of the velocity dependence.

These experiments have led to the discovery of a possible means of measuring the energy lost from the crater region by wave motion. The thermocouple temperature records indicate a sudden rise of temperature at the time of impact then a long slow rise as heat is conducted from the crater region. This sudden rise must be due to energy deposited throughout the target by wave motion essentially instantly on the time scale of the measurements. It is hoped that careful analysis of the thermal conduction problem will allow the determination of energy appearing as wave motion.

This project is continuing under contract AF 04(647)-952.

5. Flow in High-Velocity-Impact Cratering

This project is concerned with determining wave propagation and material flow in high-velocity-impact cratering. The purpose is to furnish the information necessary to test and advance cratering theory and to give a detailed understanding of the general cratering problem.

Flow in cratering is, of course, intimately connected with the

the energy distribution in cratering and the two subjects cannot be separated; however, for purposes of discussion and for organization of research efforts, a division is made in the two subjects. In attempting to make the first cratering models, it became immediately evident that any quantitative information about flow which would be adequate to aid in making models, detailed or simple, was missing. It appeared that much information could be quite easily obtained and that this would surely pave the way to learning new methods for obtaining more information and applying it to understanding the general problem. Much of the work on this project has been of a preliminary nature devoted to developing techniques and instrumentation for measuring surface and subsurface flow in cratering. The various projects in this area are discussed in Sections 5.1, 5.2, and 5.3 below.

5.1 Measurement of wave propagation in high-velocity-impact cratering.

This project is concerned with measuring the characteristics and propagation of waves generated in high-velocity impact.

In this study, small barium-titanate pressure transducers were designed, fabricated, and embedded in the target area surrounding the crater. These transducers are very sensitive and reveal the passage of low-amplitude waves at large distances from the crater. Wave velocities can be easily measured, but the interpretation of amplitude data is difficult. Details of the transducers and typical output wave-forms are shown in Fig. 9. It is hoped that these devices can be accurately calibrated to yield quantitative pressure data because a reliable, small pressure-transducer is badly needed for flow mapping in impact studies. Methods of measuring the high pressures of impact are available[17] but they are not suitable for extensive experimental investigations.
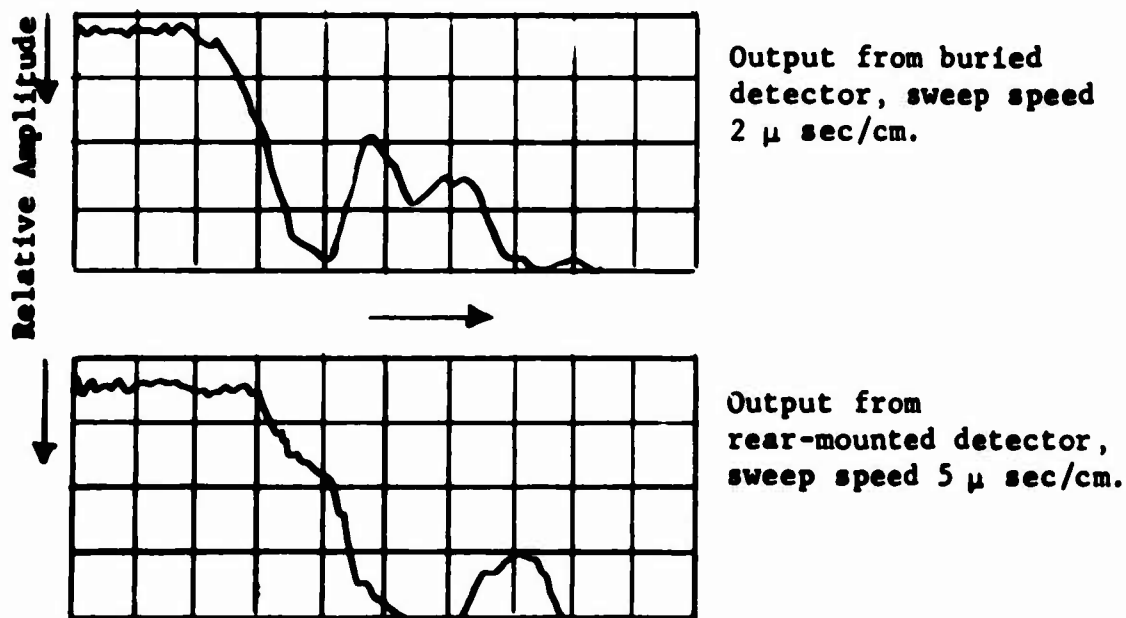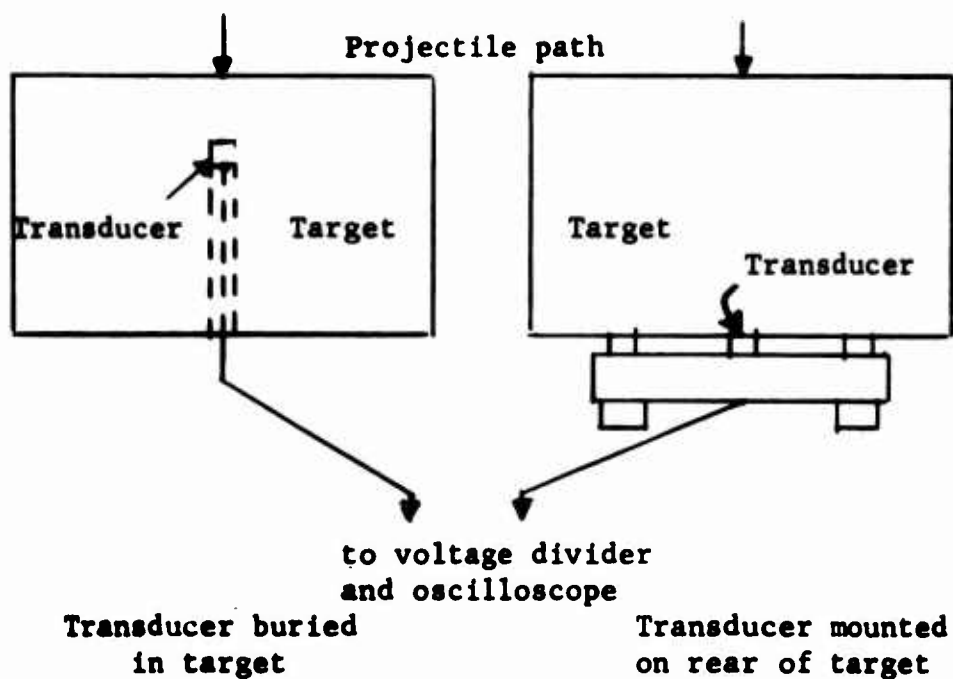
Fig. 9. Mounting of barium-titanate pressure-transducers and typical output waveforms. Transducers are 0.1 inch cubes.

They may be useful for calibrating a simple transducer.

This project is continuing under contract AF 04(647)-952 with particular emphasis on developing transducers for measuring waves in high-velocity impact.

5.2 Investigation of flow in the cratering region in high-velocity impact.

This project has been concerned with determining the magnitude and time dependence of deformation occurring in the immediate crater vicinity. First attempts to measure subsurface flow in cratering were made by embedding fine , insulated wires in small holes drilled in the crater vicinity and observing the crushing of the holes and short-circuiting of the wires to the target as the cratering progressed. These experiments lead to a knowledge of the rate of propagation of gross deformation through the target and have yielded unexpected results. It was found that cratering does not proceed at anything approaching a uniform rate, but that the projectile is very quickly dissipated and the major portion of the crater formation process occurs in a flow of long duration occurring long after the initial shock waves have passed and after the initial pellet deformation has occurred.

Figure 10 illustrates the results obtained with a wire nearly filling a hole drilled with a number 60 drill (0.040 inch diameter). The wire is so easily shorted that it detects the passage of a strong wave moving at about 4.8 km/sec. The velocity of a purely longitudinal sound wave is about 6.4 km/sec, the extensional wave travels at 5.0 km/sec, and a shear wave travels at about 3.04 km/sec in this aluminum.

Figure 11 illustrates the results obtained with a wire loosely fitted in a larger hole (0.0635 inch diameter) drilled with a number
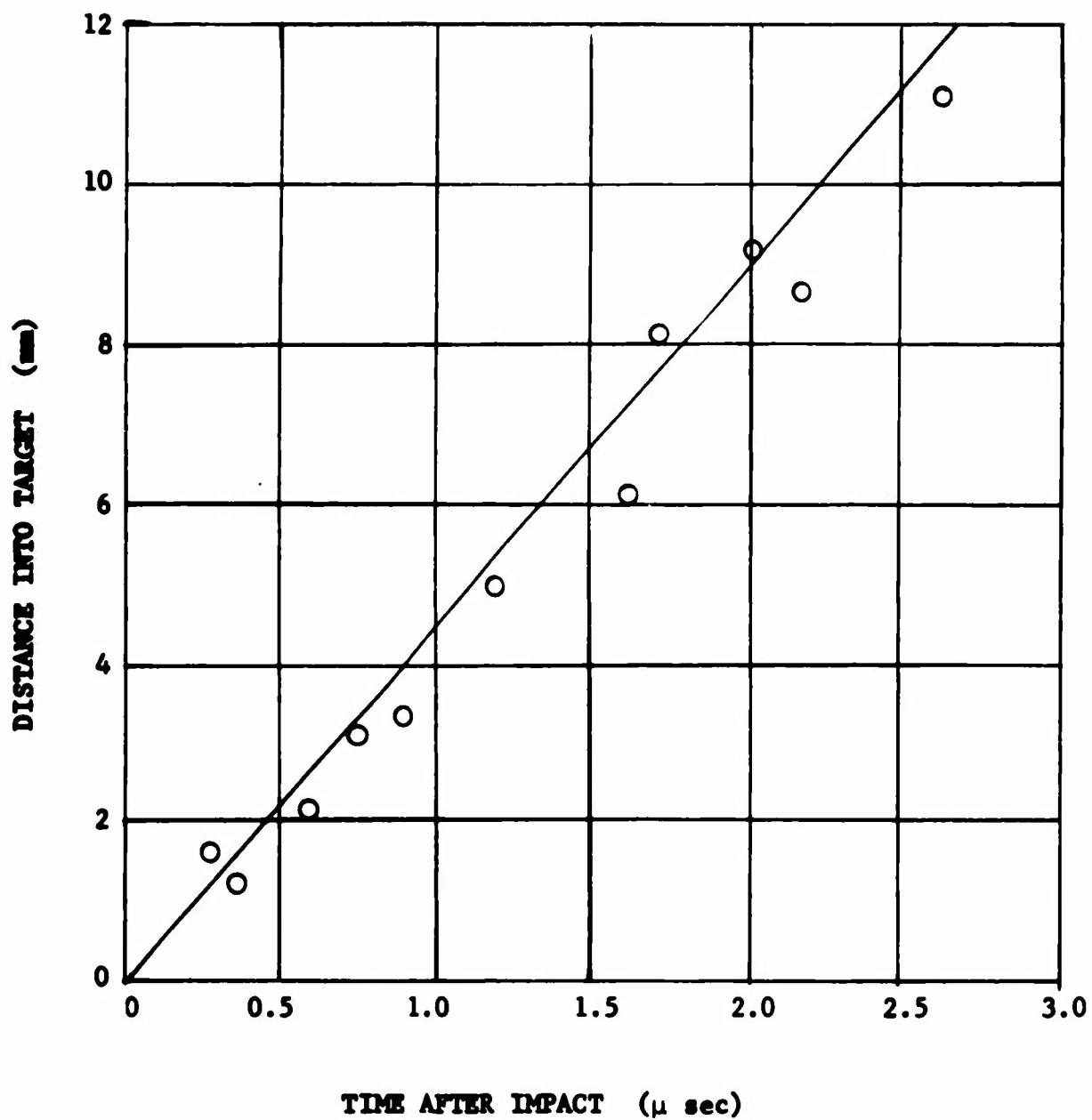
Fig.10. Response of "sensitive" detectors buried in aluminum targets. Aluminum projectiles with a velocity of 2.2 km/sec.
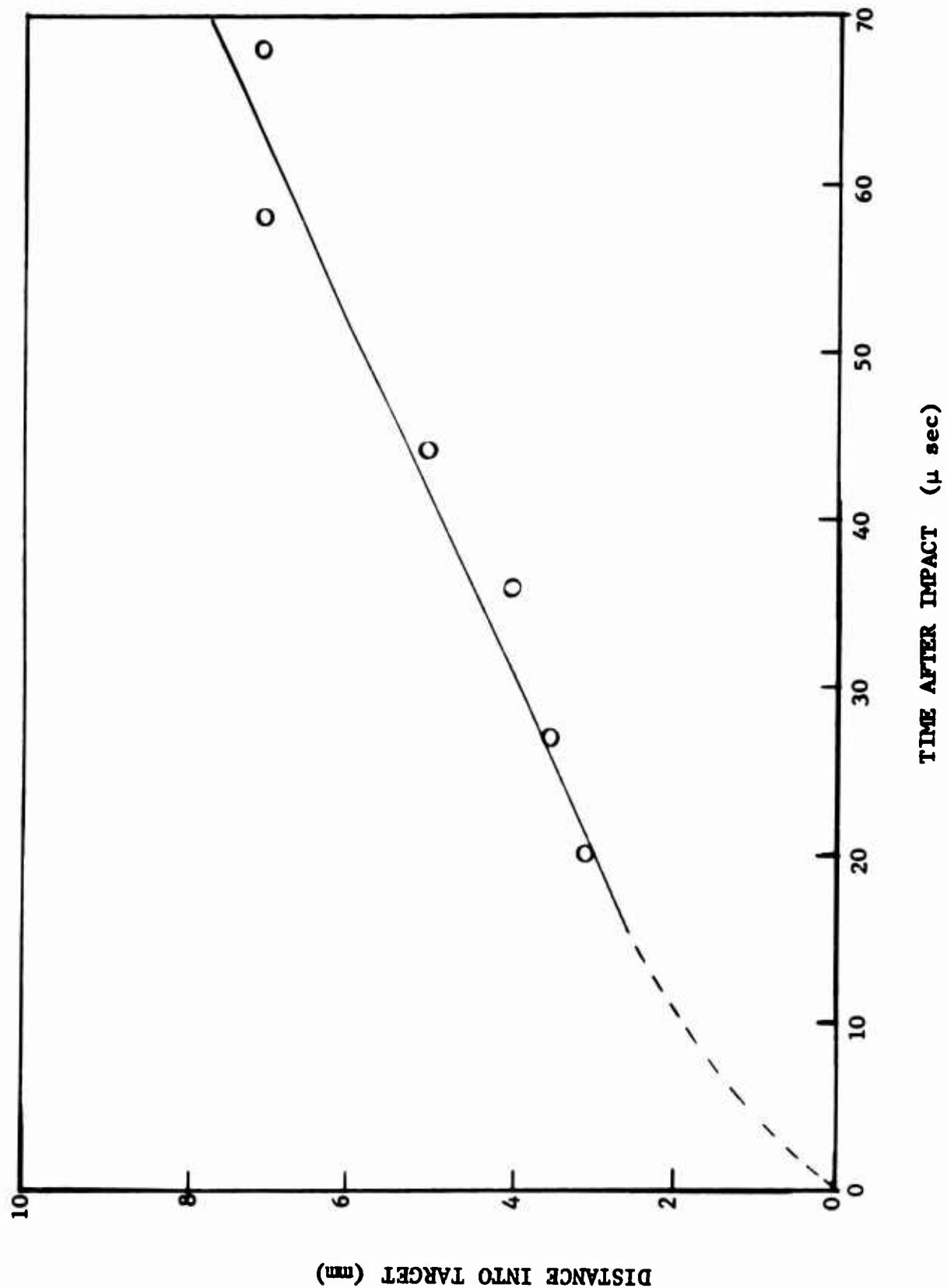
TIME AFTER IMPACT (μ sec)

DISTANCE INTO TARGET (mm)

Fig. 11. Response of "less sensitive" detectors buried in aluminum targets. Aluminum projectiles with an initial velocity of 2.2 km/sec. ...

Fig. 12. Cylindrical lead projectile impacting
into lead target.

52 drill. This detector is probably not shorted until the deformation approaches the magnitude of the hole diameter. This gross deformation moves at a steady velocity of about 0.10 km/sec after the initial high velocity.

These results stress the importance of greater understanding of the flow processes determined by strength of materials. Although the fluid processes occurring under the high-velocity conditions immediately following impact are of vital importance in determining the initial conditions for the general process, it appears very likely that the most important part of cratering, at least from the point of view of magnitude of total damage, is the late slow process determined by strength of materials. Here again, vital information is lacking. It is possible that at higher velocities this may be changed and that fluid processes will predominate; however, this is something which cannot be determined theoretically without further experimental knowledge. This again underlines the importance of setting up simplified models of the transient processes and attempting to understand the things that are occurring to attempt to fit the model to the actual physical processes observed.

This project is continuing under contract AF 04(647)-952 with work being done on the development of better methods of measuring subsurface flow and of analysing the data.

5.3 Measurement of surface flow by photography

This project is concerned with obtaining information on the transient flow occurring in high-velocity impact by means of photography of the surface during cratering.

A search of the literature of high-velocity impact indicated that no efforts had been made to look into a crater during impact and attempt to photograph the process. Shadowgraphs and silhouette photographs had been made, but these showed almost nothing of crater formation except the ejection of spray material. Because of the lack of high-speed motion picture equipment in the laboratory, it was decided to use single flash photographs and make multiple shots with a longer delay between initial impact and photograph on each successive shot. The intensity of the light flash generated by the impact indicated that photographs would have to be made in a vacuum or in a controlled atmosphere where the impact flash could be reduced below the level of the source used for photography.

Because of the well-developed techniques in spark photography, it was decided to first attempt to develop a spark light source for this work. If exposures shorter than the spark duration were needed, it was thought that a Kerr-cell shutter could be used. Light-source development proved to be a major problem. It was found to be very difficult to get a source bright enough to adequately illuminate the target through a window of the vacuum tank and still have the exposure short enough to "stop" the motion. One of the best shots is shown in Fig. 12. The target and projectile are of lead to reduce impact flash. The cylindrical projectile can be seen outlined by the impact flash. Few details of flow inside the crater can be seen; however, the work so far has been mainly concerned with exploring new techniques and it is believed that considerable improvement can be made.

Work is continuing on this project under contract AF 04(647)-952 with emphasis on the development of light sources and timing and control techniques.

6. Elastic and Plastic Wave Propagation in a Rod

This project is concerned with a detailed theoretical and experimental investigation of wave propagation in a rod and interpretation of the results in terms of measurable elastic and plastic properties of materials. The purpose of the project is to gain detailed understanding of the processes occurring in high-velocity impact in a system with simple geometry This information has intrinsic value and will also serve as a guide and check on experiment theory in the more complicated geometry met in ordinary cratering.

This project was instituted during the last month of work under contract AF 04(647)-176 but will continue as a major effort under contract AF 04(647)-952. Only a report of plans and preparations can be given at this time.

Considerable work has been done on the elastic propagation of waves in rods and other shapes, and work has been done on the propagation of plane shock waves in flat plates;[17] however, almost no work has been done on the propagation of waves in the region of plastic slip. This is probably the region of greatest interest in cratering. (See Section 5.2 above.) A preliminary analysis indicates that waves in this region can be described mathematically and related to measurable stress-strain properties of materials. Analysis indicates that the propagation of these waves can be measured in rods using strain gages.

To make these measurements, a 50-caliber gun was constructed to shoot rods up to 12 inches in length These rods will be shot against a stationary rod backed up against a hardened steel block or against a free rod. The stationary rod will be instrumented with strain gages

- 42 -

and both rods will be guided in retaining cylinders. A narrow slit of light along the axis of the rods will be observed by a photo tube to allow measurement of the velocity of the moving rod, time of contact with the stationary rod, and velocity of rebound. A schematic diagram of the equipment is shown in Fig. 13.

7. Impact Investigations using Spray Particles

This project is concerned with obtaining impact data at velocities from 10 to 25 km/sec by utilizing micron-sized spray particles generated in low-velocity impacts.

In studies made under contract AF 49(638)-462 on the spectral distribution of light generated in an impact flash, it was discovered that micron-sized particles are generated with velocities up to 10 km/sec.[8, 10, 11] In the latest measurements made under contract AF 04(647)-176, velocities up to 25 km/sec have been found. With the discovery of these particles, it became evident that they could prove to be a valuable tool for obtaining impact information. For the first time, laboratory-generated particles were available with velocities well into the range of meteor velocities. Although small, they are similar in size to much of the micro-meteorite dust which is in the solar system and provede a possible means of investigating meteor phenomena of all kinds.

A program was initiated to attempt to measure particle size and velocity accurately in order to make spray particlesuseful for impact studies. It was decided to first attempt to measure their properties by means of observations of their deceleration in a low-density atmosphere. The particles are self-luminous in an atmosphere, as are actual meteors in the earth's atmosphere, and can be observed with photomultiplier tubes. By comparing measured trajectories with theoretical trajectories
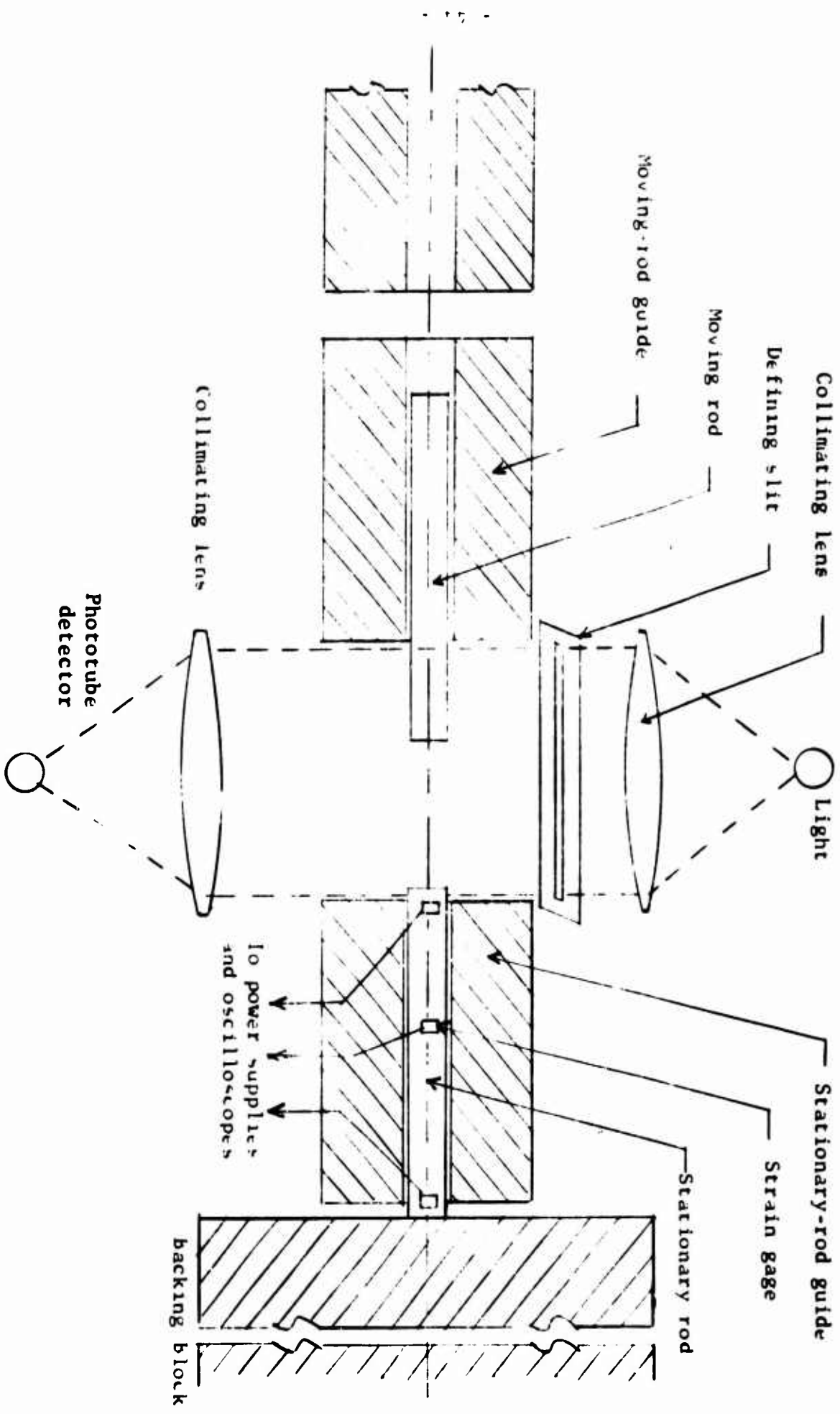
- 43 -

Fig. 13. Schematic cross-section of equipment for measuring wave propagation in a rod.

calculated for various assumptions as to particle size and mode of ablation, the particle size can be determined. Initial experiments indicate that size can be determined within a factor of 10 easily and can probably be determined within 30 per cent with four or five time and position measurements along the trajectory. Extensive trajectory calculations have been made on the University of Utah Datatron 205 computer. These are being compiled and plots made to facilitate calculation of particle properties from experimental data. This work could not be completed in time for this report. It is planned to issue a separate report on the subject of micron-sized particle trajectories under contract AF 04(647)-952.

A major part of the work on this project has been the construction of a vacuum firing range suitable for spray particle studies. The design of this range has been reported in previous quarterly reports.[7] The range is now completed and in operation.

Craters made by particles traveling at velocities of 25 km/sec have been observed under a microscope but no measurements of shape have been made. These craters range in size from 0.1 to 1.0 micron in diameter and cannot be easily measured under an optical microscope. It is believed that these craters can be best observed by making cast replicas of the crater, shadowing with evaporated metal, and observing with an electron microscope.

This project is continuing under contract AF 04(647)-952.

8. High-Velocity Accelerators and Instrumentation

Much of the money and effort spent under contract AF 04(647)-176 has gone into the design, construction, and testing of equipment for

producing and measuring high-velocity phenomena. Most of this work has been discussed in detail in the various applicable technical reports issued.

A small, arc-heated light-gas gun using lithium floride as the working gas was designed, built, and tested. Velocities up to 5 km/sec were achieved. The details of this work have been reported in Technical Report UU-6 listed on page 1. This project was abandoned because of the lack of a capacitor bank large enough to allow effective further development of arc guns. Losses are proportionately higher in a small gun and a certain minimum size is necessary for a practical gun. It would be desirable to extend this work to staged guns, but no plans to do so have been made.

A new light-gas gun has been built patterned after an older one described in Technical Report OSR-17.[9] Final assembly and testing of the gun have been temporarily suspended because of use of the light-gas-gun firing tunnel for the rod impact experiments described in Section 6.

Equipment being used on contract AF 04(647)-952 which has not been reported in detail will be discussed in future technical reports when appropriate. This includes vacuum firing range, spray-particle measuring equipment, equipment for measuring wave propagation in rods, light sources and timing equipment for photography of cratering, and transducers and equipment for measuring subsurface flow and wave motion in cratering.

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2nd	15 Sept. 1958
3rd	7 Jan. 1959
4th	1 May 1959
5th	8 July 1959
6th	Sept. 1959
7th	Dec. 1959
8th	March 1960
9th	July 1960
10th	Oct. 1960
11th	Jan. 1961
12th	April 1961

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